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Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe

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ABSTRACT

There is increasing international interest in developing low carbon renewable energy technologies. Biomass is increasingly being utilized as an energy source throughout the world. Several modern technologies have been developed that convert biomass to bioenergy. Anaerobic digestion is a mature energy technology for converting biomass to biogas, which is a renewable primary energy source. Biogas is a robust fuel that can be used to supply heat, electricity, process steam and methanol. There are vast biomass resources in Zimbabwe that have good potential for biogas production by anaerobic digestion. However, anaerobic digestion is not being optimally used as a biomass conversion technology in the country. This paper presents an overview of biogas production in Zimbabwe and outlines technical options that can be utilized to optimize biogas production by anaerobic digestion in the country.

Contents

1. Introduction

Biomass is well recognized as a fuel and ranks fourth as an energy resource providing approximately 14% of the world's energy needs [1]. Biomass accounts for as much as 67% of the total energy consumption in Africa [2]. Most of Africa's biomass energy consumption is in sub-Saharan Africa. Zimbabwe is one of the sub-Saharan African countries which rely mainly on biomass for the supply of energy. Over 76% of the country's population relies on biomass as an energy carrier [2].

The resource limitation of fossil fuels and the problems arising from their combustion has led to widespread research on new and renewable energy resources [3]. The concern with fossil fuel combustion has been the release of toxic compounds and oxides of

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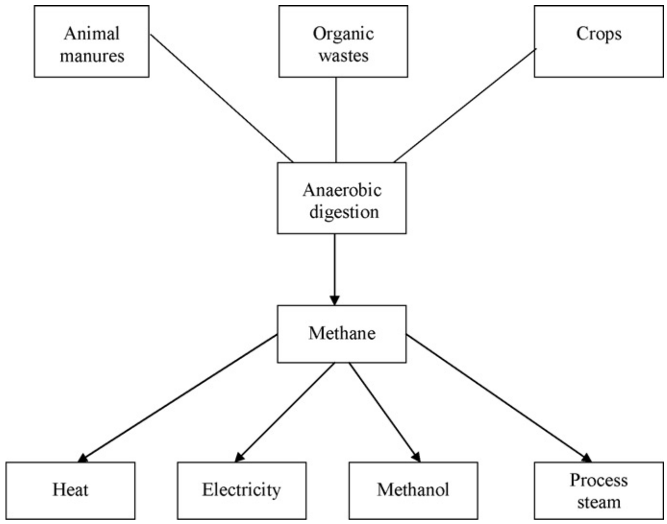

Fig. 1. Biomass conversion to bioenergy by anaerobic digestion.

nitrogen and sulfur into the atmosphere. The effects of these air pollutants are well documented. However, the greatest concern is the threat of global warming related to increasing concentrations of carbon dioxide and other upper atmospheric pollutants resulting from anthropogenic activities [4].

In response to the concerns raised above, the world has seen interest in renewable energy and related conversion technologies over the last two decades. Solar, wind, hydro and biomass resources are among the renewable energy resources that have received attention. Biomass has been attractive on the premise that it may be converted to a variety of energy forms such as heat, steam, electricity, hydrogen, biogas, ethanol and methanol [4]. In particular, biogas is distinct from the other energies on two fronts. Firstly, it is a high methane fuel, and methane is an ideal fuel as it is comparatively clean. Secondly, biogas is important in controlling and collecting organic waste material and producing fertilizer and water for use in agriculture. In addition, biogas has no geographical limitations and the technology of producing it is relatively not sophisticated [3]. Anaerobic digestion is a mature technology for converting biomass to energy. The conversion of biomass to bioenergy by anaerobic digestion is shown in Fig. 1.

This paper attempts to discuss technical options for biogas production and their benefits with a view to propose a strategy for optimizing biogas production as an energy source in Zimbabwe. The idea is to promote CO_2-neutral technologies and effective methods for treatment and disposal of organic wastes as useful renewable energy. The implementation of biogas-based energy programs will not necessarily be the panacea to the country's energy problems but it will bring insights into options available for improving energy supply in the country.

2. Principles of anaerobic digestion

Methane can be produced from biomass by either thermal gasification or biological gasification. Biological gasification is commonly referred to as anaerobic digestion. The process is carried out by a consortium of several different anaerobic bacteria. The process takes place over a wide range of temperature from 10 °C to over 100 °C and at a variety of moisture contents from around 50% to more than 99% [5]. In the absence of oxygen, anaerobic bacteria ferment biodegradable matter into methane and carbon dioxide, a mixture called biogas. Biogas contains 60–70% methane and 30–40% carbon dioxide depending on the feedstock type [3]. Trace amounts of hydrogen sulfide, ammonia, hydrogen, nitrogen, carbon monoxide, oxygen and siloxanes are occasionally present in the biogas [5]. Usually, the mixed gas is saturated with water vapour.

Anaerobic digestion takes place in basically three stages. These stages have been described by Themelis and Ulloa [6]. In the first stage, complex organic macromolecules are hydrolysed into simpler soluble molecules. In the second stage these molecules are converted by acid forming bacteria to simple organic acids, carbon dioxide and hydrogen; the principal acids produced are acetic acid, propionic acid, butyric acid and ethanol. In the third stage, methane is formed by methanogenic bacteria, either by breaking down the acids to methane and carbon dioxide, or by reducing carbon dioxide with hydrogen.

3. Biomass resources for anaerobic digestion

There are abundant biomass resources in Zimbabwe which include agricultural, municipality and industrial wastes. Total biomass energy theoretically available in Zimbabwe has been estimated at 409 PJ [7].

3.1. Animal manure

There is a significant livestock population in Zimbabwe distributed across both rural and commercial agriculture sectors. These animals produce large amounts of manure, which are suitable substrates for anaerobic digestion. Animal manure has been the most common substrate for biogas production by anaerobic digestion. Estimates of quantities of manure obtainable from the various livestock species and the associated energy potential are shown in Table 1. There is need for disaggregation of these values to show the potential contribution of the animal manure to biogas production. Thus, availability of the manure for anaerobic digestion is an important factor for consideration. Due to the alternative uses of livestock manures, their availability for biogas production may vary significantly among areas, animal groupings and years [10]. In the absence of animal manure availability factors in Zimbabwe, judicious extrapolation of data in literature can be done in order to predict their potential recoverable energy through anaerobic digestion. These data are shown in Table 2.

Table 1
Livestock population, manure output and their energy potential

Species	Population[a] (000 head)	Dry dung output[b] (kg head^{-1} day^{-1})	Total annual dung output (t)	Energy value[b] (GJ t^{-1})	Total energy potential (TJ)
Cattle	5,661	1.80	3,719,277	18.5	68,807
Sheep	566	0.40	82,636	14.0	1,157
Pigs	222	0.80	64,824	11.0	713
Goats	2,380	0.40	347,480	14.0	4,865
Poultry	23,548	0.06	515,701	11.0	5,673

[a] Mean from 1970 to 1999 for cattle, sheep, pigs and goats [8], and from 1989 to 1997 for poultry [9].
[b] *Source*: Ref. [7].

Table 2
Biogas yield from animal manures

Species	Total annual dry dung output (t)	Availability factor[a]	Total dung available (t)	Biogas yield factor[a] (m^3/t)	Total biogas yield (m^3)
Cattle	3,719,277	0.45	1,673,675	281	470,302,675
Sheep	82,636	0.35	28,923	120	3,470,760
Pigs	64,824	0.80	51,859	649	33,656,491
Goats	347,480	0.35	121,618	120	14,594,160
Poultry	515,701	0.70	360,991	359	129,595,769

[a] *Source*: Ref. [7].

Table 3
Classification of municipality solid waste in Zimbabwe [11]

Type of waste	Waste description
Household waste	Organic kitchen wastes, sweepings, rags, paper, cardboard, plastic, bone, metals
Commercial refuse	Sources include markets, shops, offices, restaurants, warehouses, hotels
Institutional refuse	Sources include schools, government offices, hospitals, religious buildings
Street sweepings	These consist of sand, stones, litter
Industrial waste	From processing and non-processing industries and utilities. They consist of packaging materials, food wastes, discarded metal, plastic, textiles, fuel burning residuals

3.2. Municipality solid waste

Various organic wastes from households and municipal authorities provide municipality solid wastes (MSW), a potential feedstock for anaerobic digestion. One of the most effective processes for getting rid of organic waste material and at the same time providing much needed energy is anaerobic digestion [3,5]. When used in a fully engineered system, anaerobic digestion not only provides pollution prevention but also allows for energy, compost and nutrient recovery [5]. Worldwide there are approximately 150 anaerobic digestion plants in operation using MSW or organic industrial waste as their principal feedstock [5].

In Zimbabwe, as elsewhere in the Third World, information on the generation and types of waste is scanty [11]. Studies have shown that generally municipal authorities collect more than 82% of the waste generated daily [11]. Per capita MSW generation has been estimated at about 0.5 kg/day, although this varies from city to city. The total population of the 19 main towns in Zimbabwe was 3,392,144 in 2002 [12]. This indicates a potential to produce about 1696 t of MSW per day.

The classification of MSW in Zimbabwe is shown in Table 3. Estimated quantities of daily waste produced and collected in 13 towns are shown in Table 4. The total MSW produced per year in these towns is 552,975 t with 500,415 t collected.

Municipality solid waste consists of several different fractions, both of organic and inorganic nature. The major fractions of MSW are paper, cardboard, putrescibles, miscellaneous wastes and plastics. Separation of MSW into the putrescible organic fraction has been known to provide the best quality feedstock for anaerobic digestion [5]. The content of putrescibles in MSW varies and in Zimbabwe has been reported to range from 10% to 45% [11]. Putrescibles can generate about 128 m^3 biogas/t [13].

3.3. Sewage sludge

Worldwide the anaerobic stabilization of sewage sludge is probably the most important anaerobic digestion process [14]. In Europe, typically between 30% and 70% of sewage sludge is treated by anaerobic digestion [5]. In developing countries, anaerobic digestion is in most cases the only treatment of waste water. All the major cities in Zimbabwe treat their sewage sludge by anaerobic digestion. The anaerobic digestion of sewage sludge provides significant benefits as it leads to the production of energy in the form of biogas.

The four major towns in Zimbabwe, which are: Harare, Mutare, Masvingo and Bulawayo, generate 300,000; 30,000; 16,800 and 35,000 t/day of sewage, respectively [15]. Biogas yields from anaerobic digestion of sewage sludge can vary from 250 to 350 m^3/t of organic solids [13]. Thus, there is potential to produce substantial quantities of biogas from sewage sludge in the country.

3.4. Crops

There are no crops grown in Zimbabwe specifically for anaerobic digestion to produce biogas. However, there are several million tonnes of agricultural crop residues produced each year. In some studies [7], these have been estimated at over 10 million tonnes, and are disposed through different ways. These crop residues have a high potential as a bioenergy resource and can provide over 123 PJ of energy per year [7]. In spite of the new methods for converting crop residues into energy, much of the available residues in Zimbabwe are still disposed by burning. In some cases, the residues are used for domestic energy supply by direct combustion, mostly in open fires.

A number of crops demonstrate good biogas potentials. In fact, all C_4 plants have very good growth yields and produce large

Table 4
Estimated daily waste produced and collected [11]

Town	Estimated production (t)	Estimated collected (t)
Harare	660	588
Bulawayo	413	404
Kadoma	40	36
Masvingo	50	47
Chinhoyi	40	33
Marondera	38	36
Chegutu	42	36
Chitungwiza	160	136
Bindura	18	12
Kariba	14	11
Norton	16	15
Karoi	16	10
Shurugwi	8	7
Total	1,515	1,371

amounts of biomass. Several crop residues have been shown to be suitable for anaerobic digestion and these include cotton wastes [16], maize and rice residues [17]. However, high lignin content in some straws and other residues can lead to poor biodegradability and low biogas production.

4. Generation and utilization of biogas in Zimbabwe

Anaerobic digestion to produce biogas has been practiced in Zimbabwe for some time now. Data in Table 1 show the livestock population and the quantities of manure that are produced. Traditionally, cattle and pig dung have been used as the main feedstock for anaerobic digestion. There are more than 400 bio-digesters installed in Zimbabwe with a capacity of between 3 and 16 m^3. However, data on the performance of these digesters are scanty. The units are located at schools, rural homes and selected industries. The biogas produced is used for household chores such as cooking. The extent of biomethanation in Zimbabwe has been estimated at only 8% of the potential [15].

The biogas produced at sewage treatment plants is not used for commercial purposes at all. A small share of the gas is in some cases used to preheat the digesters, whilst most of the gas is vented into the atmosphere. This represents wastage of energy as well as underutilization of an energy resource. There is no known anaerobic digestion of crops for energy purposes in Zimbabwe.

5. Technical options for optimizing biogas production

There are several technical options that can be pursued in order to enhance biogas production in the country. These options can be divided into two areas, one focusing on improving feedstock supply for anaerobic digestion, and the other on possible technological interventions.

5.1. Anaerobic digestion of MSW

As stated earlier, there are large quantities of MSW produced in Zimbabwe each year. There are different treatment processes for MSW. In many cases the options available are either burying them in landfills or burning them. Traditionally in Zimbabwe, these wastes are dumped in landfills, although at times they are burnt. The deleterious environmental effects of these practices are well known. For example, large volumes of methane and carbon dioxide are produced by anaerobic digestion of MSW in landfills and escape into the atmosphere. When methane is allowed to escape into the atmosphere, it has a global warming potential estimated to be 23 times greater than that of the same volume of carbon dioxide [18].

One of the most effective processes for getting rid of organic MSW and at the same time providing energy is anaerobic digestion in designated plants [3]. Worldwide, there are approximately 150 anaerobic digestion plants in operation using MSW or organic industrial waste as their principal feedstock [5]. The collection of about 500,415 t of MSW per year points to the need to develop biogas technology in Zimbabwe that utilizes this resource. Taking an upper limit of 45% organic matter content [11], MSW can supply about 225,187 t of feedstock for anaerobic digestion per year. Using a biogas yield of 128 m^3/t [13], this translates to 28,823,936 m^3 of biogas produced per year. However, there are inevitable losses of biogas during anaerobic digestion, and these have been estimated at around 6% in some studies [13]. Thus, the net biogas production per year from anaerobic digestion of MSW in Zimbabwe can be estimated at around 27,094,410 m^3. This is a vast energy resource that can improve the energy supply in the country.

An alternative method to obtain energy from MSW will be to capture biogas produced in landfills. The principal bioreaction in landfills is anaerobic digestion that produces biogas, also known as landfill gas in this case. Willumsen [19] reported that as of 2001 there were about 955 landfills in the world that recovered biogas. The landfill gas is used to operate generators which range from 0.3 to 4 MW. Regrettably, there are no gas wells in Zimbabwe that capture landfill gas. Assuming that all the 500,415 t of MSW produced per year are landfilled, and using a landfill gas yield of 62 m^3/t of MSW [20], a total of 31,025,730 m^3 of biogas can be generated in landfills. This is equivalent to about 1,706,415 m^3 of methane. At least some of this gas can be captured through gas wells and be used to supply energy. For comparison purposes, Denmark and the US capture 20,000 and 2,600,000 t of methane per year.

5.2. Anaerobic digestion of sewage sludge and industrial waste water

Anaerobic digestion of sewage sludge is already being practiced in Zimbabwe. This is the most dominant method for waste-water treatment in the country. The use of anaerobic digestion for sewage sludge stabilization is well established. Worldwide, waste-water treatment generates 10% of the global anthropogenic methane [6]. As already stated, the issue of concern is that most of the gas produced at sewage treatment plants in Zimbabwe is lost into the atmosphere. The technical option is to capture the biogas and use it to generate energy.

Substantial amounts of organic wastes are produced from industry each year. Most of the wastes from the food industry have good biogas potential, but there are no known anaerobic digestion plants for these wastes in Zimbabwe. Thus, there is need for anaerobic digestion of organic industrial waste. Worldwide, anaerobic digestion of industrial waste waters is becoming a standard technique.

5.3. Co-digestion

Until quite recently anaerobic digestion was a single substrate, single purpose treatment [14]. Throughout the years the limits and possibilities of anaerobic digestion have been better known and this has led to the development of the co-digestion technology. Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. Co-digestion offers several ecological, technological and economic advantages. Some of the merits of co-digestion are as follows [14]:

- It provides improved nutrient balance from a variety of substrates which helps to maintain a stable and reliable digestion performance and produce a good fertilizer quality of the digestate.
- Provides for optimization of rheological qualities when wastes with poor fluid dynamics, aggregating wastes, particulate or bulking materials and floating wastes can be much easier digested after homogenization with dilute substrate such as sewage sludge or liquid manure.
- Agricultural biogas production from manure alone (which has a relatively low gas yield) is economically not viable at current oil prices. Addition of co-substrates with a high-methane potential increases gas yields.

Co-digestion provides an opportunity to optimize biogas production in Zimbabwe, particularly in rural areas where quantities of animal manure might not be enough for sustained production throughout the year. The possibility to use energy crops as co-substrates offers a viable option. A number of crops demonstrate good biogas potentials. For example, the biodegradability of some sorghum varieties exceeds 90% with corresponding

methane yields of 0.39 m^3 per kg organic matter as ash-free dry weight [4]. Other crops such as Sudan grass [14], Napier grass and water hyacinth [4] are also good co-substrates. Maize has also been reported to be a popular co-substrate in Germany [14]. It is also worth noting that water hyacinth is a perennial problem in Zimbabwean dams and its use as a co-substrate in anaerobic digestion converts it from a weed to an energy source. The benefits of energy crops become more apparent when these crops are grown on fallow land or in marginal areas not normally used for food production.

5.4. Centralized anaerobic digestion

The concept of co-digestion has been taken further and developments in agricultural waste digestion have produced the concept of centralized anaerobic digestion (CAD). In CAD, many farms cooperate to feed a single large digestion plant with a variety of co-substrates. The substrates used are mainly agricultural manures and biogenic waste materials from industry [5]. The advantages of CAD are similar to those given above for co-digestion. Today, CAD has become a standard technology which is used in most European countries as well as in Asia and the USA [5].

CAD is a viable option for optimizing biogas production in Zimbabwe. There are benefits in using this cooperative arrangement in terms of substrate supply, economics and sustained gas supply. In addition, a single CAD plant can serve a wider community whose members would otherwise not sustain an anaerobic digestion plant on an individual process.

6. Conclusion

The optimization of biogas production in Zimbabwe cannot be viewed as an option only, but also as a viable imperative to improve the supply of renewable energy in the country. Anaerobic digestion as a CO_2-neutral energy technology is well developed. The challenge for Zimbabwe is to optimize the use of this technology as part of a strategy for sustainable energy supply in the country. Biogas is a robust fuel that can be used for all applications designed for natural gas. Literature abounds with examples of the use of biogas, such as, as a vehicle fuel and for heat and electricity generation.

In order to optimize the production of biogas in Zimbabwe, the following recommendations are made:

- Setup of anaerobic digestion plants for source separated MSW to produce biogas.
- Capture of biogas from all landfills through gas wells and followed by use of this landfill gas for energy purposes.
- Capture of all the biogas produced in sewage sludge stabilization plants and channeling the gas into the energy system.
- Promotion of co-digestion as a means to boost the biogas supply levels in the country.
- Setup of CAD plants to promote cooperative biogas production, especially in rural communities.

It is important to further point out that the above recommendations will be premised on the existence of a solid policy to promote CO_2-neutral technologies in the country.

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